Appendix F

The Role of Remote Sensing in an Ocean CO_2 Observing Plan

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F.1 Introduction

Remote sensing of the world ocean presently provides measurements of sea-surface temperature (SST), sea surface height, wind speed and direction, and ocean color, from which chlorophyll concentration and aerosol optical thickness are obtained. It is well known that satellites enable excellent spatiotemporal coverage and consistency of methodology, but they are limited by what they can measure, their resolution, and depth of penetration. Conversely, the sampling coverage that is only possible from satellite-borne sensors provides a powerful capability for extrapolating, integrating, and constraining other observations and model results.

Although the need to lobby for and defend the continuation of satellite-borne ocean-observing systems may not be as pressing as for in situ observations, it would be a mistake to take the present capabilities for granted. It is important that we acknowledge and highlight advances in the development of algorithms to improve estimation of biogeochemical variables, and that we encourage and request the development of new sensor suites. There are proposed missions (such as the Ocean Salinity Mission) that are critical to carbon observations and that would benefit from outspoken support from the carbon community.

F.2 General Background

F.2.1 Biogeochemical variables that can be measured or inferred from satellite-borne sensors

The following components of the carbon cycle and accompanying oceanographic processes can be addressed with remote-sensing observations.

Air-sea exchange of CO_2

Estimates of two major components relating to the exchange of CO_2 between ocean and atmosphere can be improved upon by using remote sensing: the air-sea gas exchange coefficient, and oceanic pCO_2. The air-sea exchange coefficient is usually parameterized using wind speed. Scatterometers provide global observations of wind speed and direction on a daily basis. Likewise improved parameterizations that use measurements of surface roughness (from which capillary wave height is estimated) from the TOPEX/Poseidon altimeter (Frew *et al.*, 1999) or from scatterometers (such as QuikSCAT or

SeaWinds) may give a more direct value of the exchange rate than wind-based parameterizations.

Much research has gone into parameterizing the partial pressure of CO_2 in ocean water (pCO_2) with SST or salinity (Boutin *et al.*, 1999; Loukos *et al.*, 2000). The general consensus is that the relationships between SST and pCO_2 are not globally applicable and that they change in space and time (Lee *et al.*, 1998). The use of salinity, which is proposed to be measured remotely on European and U.S. satellite missions would enable the application of local relationships obtained from shipboard and moored or drifting platforms. Although chlorophyll concentration (obtained from ocean color) is often invoked as a factor determining pCO_2, the algorithms that would incorporate it are still under development.

In addition to the development of empirical relationships between pCO_2 and remotely measured oceanographic variables, the latter also provide information on oceanographic processes that control patterns and variability of carbon fluxes, such as water masses, upwelling, subduction, or biological productivity.

Primary production

The rate of carbon uptake or photosynthesis is a process of major importance as it draws down carbon in surface waters. The advent of ocean color measurements, from which chlorophyll concentration can be derived, has fueled the development of a suite of primary production (PP) models that use chlorophyll concentration, irradiance, and SST (all measured remotely). There are several types of PP models with varying degrees of complexity (Behrenfeld and Falkowski, 1997). At present, they provide estimates within a factor of two when compared with in situ rates of carbon uptake determined with ^{14}C uptake measurements (Campbell *et al.*, submitted). Research is ongoing to improve their performance. All PP algorithms require a measure of irradiance at the ocean surface (photosynthetically available radiation from 400–700 nm or PAR) and its decrease with depth (which can be estimated with PAR and the light attenuation coefficient, k), both of which are also accessible from ocean color.

New or export production

Although models exist to estimate primary production, our estimations of new or export production carry an additional level of uncertainty. The methods used address various aspects of the export process. Most estimates utilize a relationship between f-ratio and SST or primary production, nitrate or chlorophyll concentration (Sathyendranath *et al.*, 1991; Laws *et al.*, 2001). These approaches can be used with satellite-derived measurements, but will only be as good as the primary production estimate and the inferred f-ratio, which may vary regionally and with time. Other potential approaches directly address the supply of nitrate via heat fluxes (and the relationship with nitrate) or precipitation. Other estimates are based on nutrient uptake as derived from changes in SST (Goes *et al.*, 2000) or heat content (Carr *et al.*, 1999).

Community structure

Information on the role of community structure and export fluxes can be employed for those situations in which one or more functional groups can be identified with space-based observations. A few organisms have been identified from space, namely, coccolithophorids (Brown and Yoder, 1994) and the diazotroph *Trichodesmium* (Subramaniam *et al.*, 1999). The concentration of calcium carbonate ($CaCO_3$) is derived routinely from ocean color and work is ongoing to improve algorithm implementation for both SeaWiFS and MODIS (Gordon *et al.*, in preparation). Other efforts are underway to distinguish *Phaeocystis* and diatoms, usually with the help of one or more sensors and ancillary in situ information. The differences in pigmentation are not readily distinguishable remotely, as they require fourth-order differentiation of the absorption spectra of cultures in laboratory flasks. The groups that have been distinguished so far are characterized by their unique "packaging" characteristics, such asthe coccoliths of *Emiliana* and the gas vesicles of *Trichodesmium*.

Partitioning of carbon species

It is important that we distinguish the partitioning of carbon species (POC, DOC). A recent study has provided an estimate of POC using reflectance measurements (Stramski *et al.*, 1999). Although applied to the Southern Ocean, this method may be extended, with proper in situ validation, to the global ocean. DOC is a much trickier problem. Although there are algorithms to quantify colored dissolved organic matter (CDOM) (e.g., Hoge and Lyon, 1999), the relationship between CDOM and DOC is not straightforward (Nelson *et al.*, 1998).

Photochemistry

Dissolved organic carbon undergoes transformation due to the effect of visible and ultraviolet light, generating dissolved inorganic carbon, DIC (Blough, 1992). This photochemical conversion of dissolved organic matter can also be addressed with remote sensing information (Cullen *et al.*, 1997, 1999; Johanssen *et al.*, 2000). Models with an experimental basis, comparable to those of primary production, utilize measurements of reflectance (which provide concentrations of CDOM) and of irradiance to derive the rate of destruction of DOC and production of DIC. Laboratory-derived action spectra, modeled irradiance, and estimated CDOM vs. total absorption can be used to quantify rates of photochemical transformation (Cullen *et al.*, 1999).

Aerosol concentrations

Aerosol concentrations can be measured using reflectance sensors designed for other applications, such as AVHRR, SeaWiFS, or MODIS, or those designed specifically for aerosols such as TOMS or MISR. Atmospheric aerosols are diverse, including smoke and dust, and methods are being developed to distinguish between the various absorbing components. A special issue of the *Journal of Geophysical Research* on the Asian Dust Outbreak of February 2000 was published in August 2001 (e.g., Husar *et al.*, 2001). Tracking dust deposition patterns can provide an estimate of the supply of terrestrial iron to the ocean surface, with consequences for biological carbon uptake.

Small-scale variability

Satellites also provide an unprecedented opportunity to quantify variability and processes that are unresolved by coarse models and necessarily inadequate sampling campaigns. The quasi-synoptic coverage is an amazing benefit, even considering the loss of data due to cloud coverage in sensors that measure light. The TOPEX/Poseidon altimeter enables improved quantification of eddies for biogeochemical applications (Siegel *et al.*, 1999) and for ocean circulation models. Coastal processes, which require higher spatial and temporal resolution than is usually possible from sun-synchronous sensors, can benefit from geo-stationary platforms and multispectral reflectance measurements. The proposed NASA-NOAA Special Events Imager (SEI) would fly on a GOES satellite in the early 2000s; the spatial resolution would be 300 m and repeat sampling would occur within minutes.

F.2.2 Relevant Existing Remote-Sensing Missions

Table F-1 reviews the major satellite sensors currently in orbit, the variables they are designed to measure, their sampling resolution, and the accuracy of their measurement.

F.3 New Developments

F.3.1 Sensors

Multiple sensors that measure the same variable are presently space-borne, or will be shortly. Combining data from multiple sensors (specifically ocean color, SST, and scatterometers) will lead to enhanced spatiotemporal coverage. Likewise, newly measured properties, such as natural fluorescence, will contribute to our understanding of the carbon system. Microwave data to infer SST are not impeded by cloud cover and will increase coverage, especially when merged with existing infrared measurements (Wentz *et al.*, 2000).

F.3.2 Programs

The International Ocean-Colour Coordinating Group (IOCCG) has a mandate to act as liaison and communication channel between users, managers, and agencies in the ocean color arena (`http://www.ioccg.org/about.html`). Primary objectives include training, advocating the importance of ocean color data, and facilitating the merging and access to ocean color data.

Table F-1: Major satellite sensors in orbit and their characteristics.

Sensor[1]	Variable	Resolution[2]	Accuracy[2]
AVISO merged TOPEX/Poseidon and ERS1/2	SSH	0.25 deg, 10 day	5 cm
QSCAT	Wind vector	0.5 deg, 12 hour	0.5 m/s
SSM/I	Wind speed	0.5 deg, 12 hour	1.3 m/s
AVHRR	SST	9 km (Pathfinder), 12 hour	0.5C
TMI	SST	0.5 deg, 3 day	0.6C
SeaWiFS	Chlorophyll PAR $CaCO_3$ CDOM Aerosols	9 km, 8 day	10%
MODIS	SST Chlorophyll $CaCO_3$ CDOM Primary production Aerosols Fluorescence	4.6 km, daily–weekly	
MISR	Aerosols	17 km, 9 days	

[1]Acronyms: AVISO—Archiving, validation and interpretation of satellites oceanographic data; AVHRR—Advanced very high resolution radiometer; ERS—European remote sensing satellite; MISR—Multi-angle imaging spectro-radiometer; MODIS—Moderate-resolution imaging spectroradiometer; QSCAT (or QuickScat)—Quick scatterometer; SeaWiFS—Sea-viewing wide field-of-view sensor; SSM/I—Special sensor microwave imager; TMI—Tropical microwave imager.

[2]The resolution and accuracy requirements are for merged and standard mapped data products. Actual spatial resolution of the instrument is higher along track and less between tracks. The temporal resolution provided is approximately that necessary to cover the world ocean. The resolution also corresponds to data points acquired. Actual observations are much less in the case of infrared and visible observations such as ocean color or radiometer because of cloud cover. It takes at least three ocean-color sensors (with different mission coverage characteristics) to cover 60% of the world ocean in 4 days given climatological cloud cover (Gregg and Woodward, 1998).

These goals are relevant to experienced users and to a community that does not wish to specialize in remote sensing.

NASA's program for Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) has four primary activities: (1) data product validation, (2) sensor calibration, (3) data merger algorithm evaluation, and (4) satellite data processing. More information can be found at `http://simbios.gsfc.nasa.gov/` and in McClain and Fargion (1999).

F.4 What Is Missing?

Programs for technology development (such as SBIRs), especially for field instrumentation, are not as well managed within NASA (and perhaps other agencies) as they should be. It is important that this key aspect of observational science not be neglected. A concerted and collaborative effort of all agencies could provide major breakthroughs in our measuring capabilities.

F.5 Conclusions

Satellite data are neither perfect nor complete. Though the standard products of most sensors are of high quality (in most places), compound products (such as PP, new production, functional type, etc.) should not be taken at face value.

It is extraordinarily important that emphasis be placed on satellite observations concurrently with field programs. Satellites can provide:

- The best possible coverage in space and time, thus enabling extrapolation of point or line measurements. Satellites provide, in fact, the only possibility for global ocean measurements.
- A context for oceanographic processes both in space and time (e.g., presence of eddies or plumes, shifts in wind direction) that can lead to improved understanding of the underlying oceanography.
- Data to force, assimilate into, or constrain models.
- An estimate of scales of variability that are not accessible except via process studies (e.g., eddies, wind events, bloom dynamics).

It is important that the seagoing community request new and improved sensors. For example, the salinity mission will lead to better determinations of global sea surface pCO_2 patterns and variability.

Satellite data cannot replace field observations, but they play a vital complementary role. Both field and remote-sensing approaches are necessary to tackle the goals of understanding and quantifying global patterns in carbon dynamics.

F.6 References

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